

UV PRE-IONIZED RAIL-GAP SWITCH FOR STACKED BLUMLEIN PULSE GENERATORS *

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Abstract

Stacked Blumlein Pulse Generators comprised of parallel-plate transmission lines are potentially a useful pulse-power architecture for high-gradient, compact, electron-beam accelerators and other applications. Such pulse generators require a low-inductance, fast (<5ns) switch per stage to erect the stack and produce the desired output pulse. We are developing a rail-gap switch tightly integrated with the stack for this application. We employ ultraviolet light (UV) to pre-ionize the switch, which facilitates prompt, low-jitter, and potentially multi-channel operation. A novel aspect of our switch is that the source of the UV is a conventional Xenon flashlamp. This allows variation of the switch pressure and gas without affecting the flashlamp operation. We can operate our switch in either triggered or self-breaking mode. Here we present initial results of a two-stage, stacked Blumlein operating in self-break mode. We compare the switch performance to gas-switch scaling laws with respect to resistive-phase risetime and trigger delay as a function of gas density, gap-length, and gap-voltage.

I. INTRODUCTION

We are developing a high-voltage pulse generator technology based on charged-line, parallel-plate, Blumlein transmission lines. Parallel-plate transmission lines are particularly well suited for stacking to achieve much higher output voltages than we can achieve with single stages. Such Stacked Blumlein (SBL) pulse generators have a wide range of pulsed power applications including particle accelerators and EMP generators.

The output pulse shape of an SBL is ideally a rectangular pulse when coupled to a matched load. However, in practice the actual pulse shape depends on the actual properties of the transmission line structure, actual properties of the load, and perhaps most importantly, the characteristics of the switch used to discharge each stage. All charged-line pulse generators require such a switch and in many cases this switch is the main limiting factor in performance. A wide variety of

switches are possible. At lower voltage levels, semiconductor switches and optical switches are viable. Since we are interested high-voltage per stage (up to 100kV) and line impedances that require kiloamp level switch currents, pressurized spark-gap switches remain one of the most viable alternatives.

II. SWITCH DESIGN

When designing a pulse generator with rise-times approaching 1ns, it is important to consider the design of the switch and the transmission line in an integrated way. To design our switch, we considered two widely known spark-gap scaling laws. The scaling law for a spark gap resistive-phase rise-time is given by[1]

$$t_r(\text{ns}) = \frac{1894}{(NZ)^{1/3} E^{4/3}} \left(\frac{\rho}{\rho_0} \right)^5 \quad (1)$$

where N is the number of switch channels, Z is the line impedance in ohms, E is the electric field in kV/cm, ρ is the gas density of the switch operating gas, and ρ_0 is the gas density of air at STP. We require a low-jitter switch so our design will scale to larger systems with many more stages. To achieve low jitter, the switch delay time (time after trigger or time after breakdown voltage is exceeded) must not be too much longer than the required switch risetime. We consider the scaling law for switch delay time[2]

$$t_h(\text{ns}) = 9.78 \times 10^{13} \frac{\rho^{2.44}}{E^{3.44}} \quad (2)$$

We solve these two scaling laws for E and obtain an expression for the required gas density as a function of switch rise-time and switch delay.

$$\rho = \left[\frac{2.437 \times 10^{-2} t_h^{291}}{((NZ)^{1/3} \rho_0 t_r)^{3/4}} \right]^{2.985} \quad (3)$$

Then we go back to Eq. (1) or Eq. (2) and solve for the electric field. If we choose a voltage, then we also have chosen the gap and the switch design is complete with regard to gap, voltage and operating pressure for a given

* This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

Report Documentation Page			Form Approved OMB No. 0704-0188	
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1. REPORT DATE JUN 2005	2. REPORT TYPE N/A	3. DATES COVERED -		
4. TITLE AND SUBTITLE Uv Pre-Ionized Rail-Gap Switch For Stacked Blumlein Pulse Generators			5a. CONTRACT NUMBER	
			5b. GRANT NUMBER	
			5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)			5d. PROJECT NUMBER	
			5e. TASK NUMBER	
			5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Lawrence Livermore National laboratory, PO Box 808, L-485 Livermore, CA, USA			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)	
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited				
13. SUPPLEMENTARY NOTES See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013.				
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15. SUBJECT TERMS				
16. SECURITY CLASSIFICATION OF: a. REPORT unclassified			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 4
b. ABSTRACT unclassified			c. THIS PAGE unclassified	
19a. NAME OF RESPONSIBLE PERSON				

gas. We have used this solution of the gas switch scaling laws to examine various aspects of switch design.

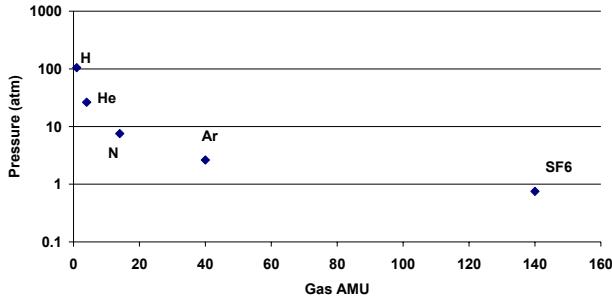


Figure 1. Required pressure as a function of gas AMU for fixed switch parameters.

In Figure 1, we show the required gas pressure of some common switch gases for a fixed set of line and switch parameters ($t_r=5\text{ns}$, $t_h=200\text{ns}$, $Z=13\text{ ohms}$) and we assume 10 channels. We see that heavier gases allow lower, more practical operating pressures. We chose SF_6 as our baseline gas for this reason.

We can also see how risetime affects switch design.

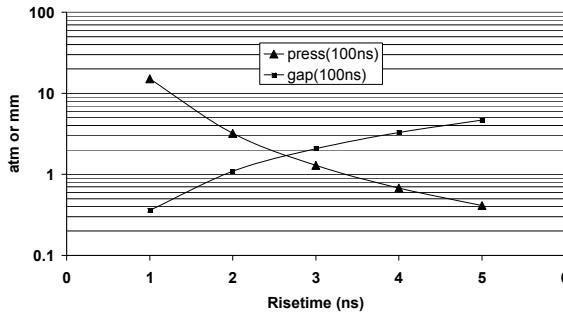


Figure 2. Switch gap and pressure as a function of desired risetime for fixed switch delay time.

We see in Fig. 2 that for faster risetime, we must have higher pressure and decreased gap-size. We can define a “zone of practicality” where switch pressure is 1-10 atm and switch gap is 1-10 mm. Gaps less than 1mm would be hard to realize with good accuracy over many switches and pressures less than 10 atm. are obviously more practical.

III. UV ILLUMINATION

It is well known that UV illumination of spark-gap switches improves jitter performance [3]. For our switch design we have chosen conventional Xenon flashlamps as the source of UV. Use of flashlamps is well suited to our geometry. We can place the lamps close to the switch electrodes and the lamps have their own sealed gas environment. Changes in the switch gas or pressure therefore do not affect the lamp operation. Lamps are much less expensive and simpler to implement than a UV laser. We believe this may be the first time where

flashlamps have been used to facilitate spark-gap operation.

IV. EXPERIMENTAL SETUP

A side-view diagram of the experimental setup is shown in Fig. 3. A CAD model of the experiment is shown in Fig. 4. A closer view CAD model of the switch end is shown in Fig. 5 and a photograph of the fielded experiment is shown in Fig. 6.



Figure 3. A side view diagram of our two-stage Stacked Blumlein pulse generator.

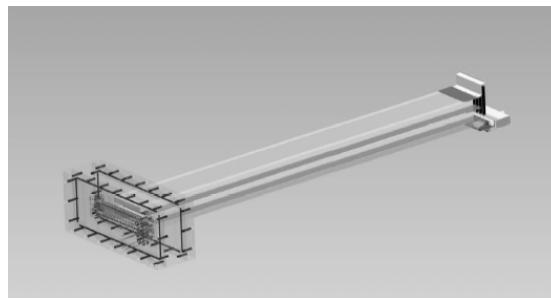


Figure 4. A full CAD model of the experimental setup.

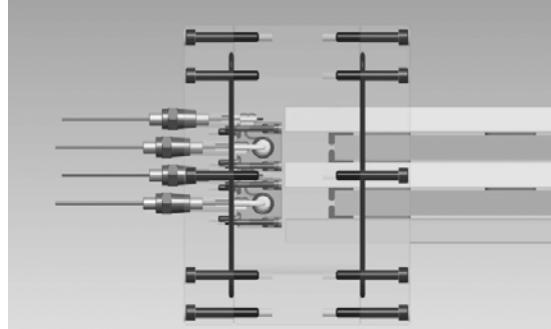


Figure 5. A CAD model showing a closer view of the gas box, switch electrodes, and flashlamps.

The stack is comprised of four layers of Duroid® [4] material with an ϵ_r of 10.2. The length of the line is 120cm yielding an expected pulse width of 26ns. The width of the line is 10 cm and the line thickness is 1.27 cm yielding an expected impedance of 14.75 ohms per layer or 59 ohms for the output impedance of the two-stage stack. The Duroid material is clad with 2oz copper and we used an oven process with conventional solder to attach the layers together both electrically and mechanically. The switch end is enclosed in a polycarbonate box to allow the switch to operate with different gas and pressure than the rest of the stack. A polycarbonate flange is epoxy-potted to the stack and

forms the pressure seal. The back cover of the gas box provides for mounting of the flashlamps along with electrical feedthroughs for the flashlamps and their triggers. The other end is the load end where we terminate the line with a matched resistive load.



Figure 6. A photograph of the completed two-stage SBL with flashlamp illuminated spark gap switches.

We designed the switch electrodes to press in between the Duroid layers. This provided us with the flexibility to easily change electrodes allowing changes in gap, electrode shape, or electrode material.

To diagnose the operation of the stack, we incorporated three voltage probes: one across each switch and one across the load. These voltage probes are comprised of 1000-Ohm resistors placed across the measurement nodes. We use a wide-band current transformer to measure the current in the probe resistor. This signal is proportional to the voltage across the probe and DC-isolated. We record these three signals on a waveform digitizer.

The stack is charged with a pulse-charge system. This system feeds the two-stage stack through a balanced network of inductors. The balanced charging network charges both stages synchronously, which is important for self-breaking switches. We are able to vary the charging speed by changing the inductor set. In practice, we varied the charging speed from 500ns down to as fast as 100ns.

The Xenon flashlamps are driven with a capacitor discharge supply. The current pulse is approximately 10 μ s. We trigger the flashlamps in advance of the pulse charge and set the delays so the stack fires near the peak of the flashlamp current pulse. On the time scale of the pulse-charging and stack firing, the flashlamp current is essentially constant.

To design the final switch electrodes, we choose target switch parameters of $t_r=2$ ns and $t_h=30$ ns. This yields a set of gaps for operation at any desired voltage. The data presented here was taken with a 1.6mm gap (20kV nominal switching voltage at 1-atm. of SF₆). In principle, this stack is capable of much higher voltage per stage by

installing larger gaps but the electrical weak point is where the pressure flange is potted to the stack. We kept the switching below 30kV to preserve the life of the stack.

V.EXPERIMENTAL RESULTS

We have operated our SBL with two electrode widths (full line width of 10 cm and a short electrode 6.4mm wide). We have experimented with different electrode profiles and have run with two gases (pure SF₆ and 15% Argon 85% SF₆) at pressures from 0-psig to 25-psig. Generally, we achieved the best results with the Argon gas mix combined with a sharpened-edge electrode on the anode side of the switch.

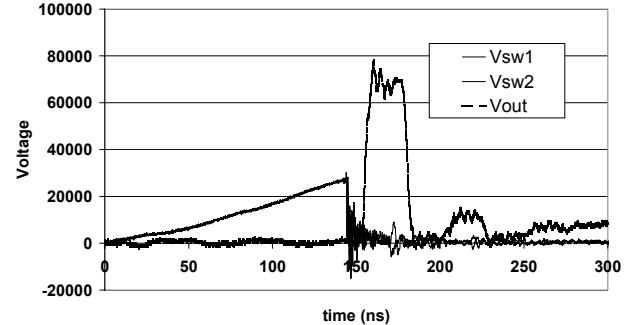


Figure 7. Typical data set showing pulse charging, switching, and output pulse.

In Figs. 7&8 we show a typical set of raw data. Voltage monitors across each switch V_{sw1} and V_{sw2} show the full pulse charge event and subsequent self-break switching. The waveforms from the two stages are directly on top of each other. The 70 kV output pulse is also shown and appears 13 ns after switching (one-way transit time). The 10 kV reflected pulse indicates that the load did not exactly match the stack impedance.

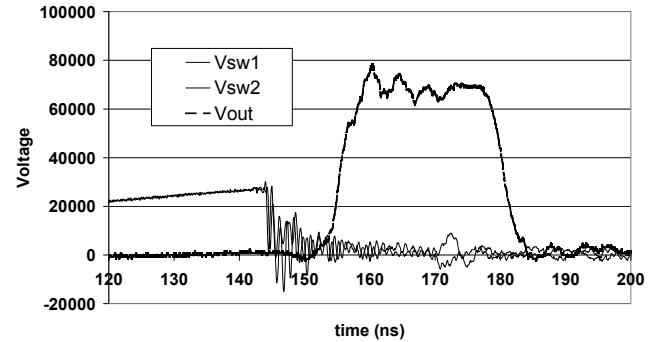


Figure 8. A zoomed in view of the same typical data set shown in Fig 7.

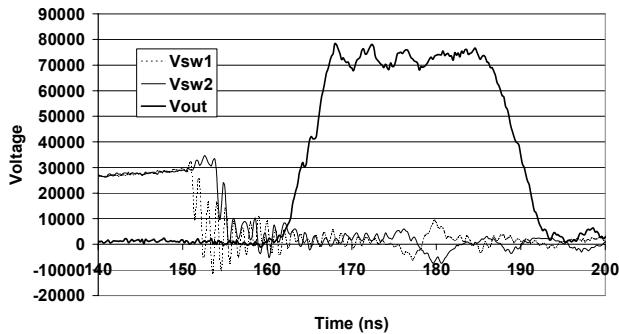


Figure 9. A dataset where the two stages fired about 2.5ns apart.

In Figure 9, we show a shot with the same conditions where the two stages fired about 2.5ns out of synchronization. This leads to a “smearing out of the output pulse rise time.

We mentioned previously that we varied electrode shape, gas mix, and flashlamp current. We found the best results with the 15% Argon mix and a sharpened electrode on the positive (anode) side of the switch. We considered switching-promptness, shot-to-shot jitter, and shot-to-shot synchronization between stages as metrics. The electrode shape and gas mix only effect the very beginning of the switching event. In Figs. 7-9, the voltage at the switch is seen to increase monotonically as it follows the pulse-charge waveform and then suddenly collapses. In the less than ideal configurations, we observe that the voltage across the switch clamps for 1-10ns before switching occurs. We identify this as a “cooking phase” where current has started to flow but the voltage has not collapsed. This situation is clearly evident in Fig. 10.

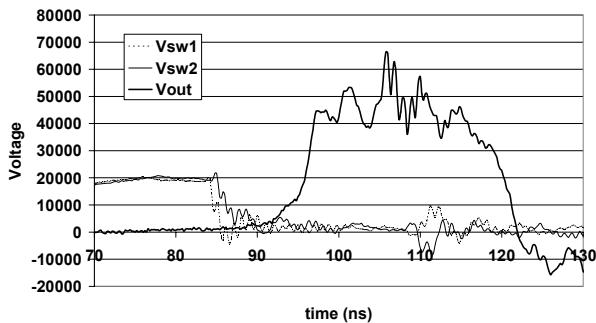


Figure 10. Sharp cathode electrode leads to non-prompt switching.

We found using a sharp electrode on the cathode side of the switch caused the longest “cooking times”. This leads to a foot at the beginning of the output pulse.

At the fastest pulse-charge speed, we observed multi-channel operation using the wide rails. We compared the output pulse to other shots where we used the narrow rails forcing single channel operation. We did not see any difference in the resulting output pulse. We expected the wide rails to provide lower inductance operation and

hence, faster risetime. This remains an open issue for further research.

VI. CONCLUSION

We have presented a design methodology for high-voltage gas switches based on widely accepted empirical scaling laws. We have used this methodology to design a switch for planar transmission line, stacked Blumlein pulse generators. We have built and tested a two stage SBL. We have also demonstrated the use of Xenon flashlamps as a source of UV to allow synchronization of self-breaking switches with low jitter without expensive or complicated trigger systems. Our pulse generator works as expected generating a 26ns pulse with a risetime in good agreement with the predicted t_r .

VII. ACKNOWLEDGMENTS

Many other people helped in the design, construction and operation of this experiment. We would like to specifically acknowledge Fred Allen for doing all the CAD design work, Wayne Jensen for the oven soldering and plastics work, Ed Gower and Joel Stanley for their assistance in the lab, Barry Smith at Advanced Photon Technology for developing the flashlamp, and Richard Miller at Titan Pulse Sciences for his discussions about gas switching.

VIII. REFERENCES

- [1] J.C. Martin, “Solid, Liquid, and gaseous Switches,” Texas Tech University Pulse Power Lecture Series, No. 30, 1981.
- [2] T.H. Martin, “An Empirical Law for Gas Switch Breakdown Delay,” in 7th Pulsed Power Conference, 1989, pp. 73-79.
- [3] T. Nitta, N. Yamada, and Y. Fujiwara, “Area Effect of Electrical Breakdown in Compressed SF₆,” IEEE Trans. Power Apparatus and Systems, vol. PAS-93, No. 2, pp. 623-9, 1974.
- [4] Duroid is a registered trademark of the Rogers Corporation, Chandler, AZ.